



---

Khan, FN, Haider, J and Persson, M (2017) Investigating tool performance and wear when simulating bandsawing of nickel-based superalloy under interrupted orthogonal turning condition. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 233 (2). pp. 515-526. ISSN 0954-4054

---

**Downloaded from:** <https://e-space.mmu.ac.uk/621335/>

**Version:** Accepted Version

**Publisher:** SAGE

**DOI:** <https://doi.org/10.1177/0954405417728310>

Please cite the published version

<https://e-space.mmu.ac.uk>

# **Investigating Tool Performance and Wear When Simulating Bandsawing of Nickel-based Superalloy under Interrupted Orthogonal Turning Condition**

**Fahd N Khan<sup>1</sup>, Julfikar Haider<sup>2,\*</sup>, and Martin Persson<sup>3</sup>**

*1. Faculty of Materials Science and Engineering, GIK Institute, Topi, Swabi, Pakistan*

*2. School of Engineering, Manchester Metropolitan University, Manchester, United Kingdom*

*3. SNA Europe, Fiskargatan 1, 53118 Lidköping, Sweden*

**\* Corresponding author**

Julfikar Haider

e-mail: j.haider@mmu.ac.uk

Tel: 0044(0)1612473804

## **Address**

School of Engineering

Manchester Metropolitan University

Chester Street, Manchester, M1 5GD

United Kingdom

## **Abstract**

The manufacturing industries still face the most challenging job at hand to machine Nickel-based superalloy, Inconel 718, efficiently and economically. In contrast to the extensive research efforts in secondary machining processes such as turning, milling and drilling, very little or no attention is paid on bandsawing of Inconel 718. The paper presents an experimental investigation of machining Inconel 718 using carbide tipped bandsaw teeth in a custom made experimental facility. Cutting forces were measured during the bandsawing operation using a dynamometer and the wear modes and mechanisms in the bandsaw teeth were investigated in a Scanning Electron Microscope (SEM). Three different feeds or depths of cut (10  $\mu\text{m}$ , 20  $\mu\text{m}$  and 30  $\mu\text{m}$ ) were employed with a cutting speed of 30 m/min during the machining tests. At smaller feed or depth of cut (10  $\mu\text{m}$ ), abrasive wear, adhesive wear and some degree of plastic deformation were identified as the governing mechanisms of tool wear. The higher depth of cut (30  $\mu\text{m}$ ) could cause cracking, chipping or premature failure of the carbide tip in bandsaw tooth. Strong welding of workpiece material to the cutting edge formed a built-up-edge (BUE), which would impair the bandsawability due to the modification of the cutting edge. The higher depth of cut significantly improved the machining performance due to the reduction in specific cutting energy. However, it was not recommended to apply higher depth of cut as there were obvious possibilities of premature tooth failure. Machining force and specific cutting energy results along with chip characteristics were correlated with the tool performance and tool wear. The results of this investigation would be helpful for bandsaw manufacturers and end users to get a fundamental understanding of the bandsawability of Inconel 718 with the carbide tipped bandsaw.

## Keywords

Bandsawing, Inconel 718, Cutting force, Wear modes & mechanisms, Built-up edge, Specific cutting energy

## 1. Introduction

Material engineers are continuously facing the challenges to develop high strength materials for demanding applications such as in aerospace industry. At the same time, the cutting tool industries are facing the challenges to machine the materials at an economic rate with high dimensional accuracy and better cut surface quality. One such material is Nickel-based superalloy Inconel 718, which is commonly employed in the aerospace, nuclear and biomedical industries, owing to its superior mechanical, thermal, and chemical properties such high yield strength, high fatigue strength, good creep and oxidation resistance at elevated temperatures. The aforementioned attractive properties of Inconel 718 alloy are also responsible for its poor machinability, making it one of the most well-known ‘difficult-to-machine’ materials <sup>1-7</sup>. The ability of Inconel 718 to retain its strength at elevated temperatures, leads to high cutting forces, which are roughly twice when cutting medium carbon steels. Inconel 718 has low thermal conductivity (11.4 W/mK) which leads to the generation of high temperature at the tool-workpiece interface. Inconel 718 has high affinity to react with almost all tool materials, leading to attrition and diffusion wear of the tool. Moreover, Inconel 718 is sensitive to high strain rate and hence rapidly work harden causing abrasive wear of the tool <sup>8-9</sup>. The presence of hard phases in the microstructure, such as carbide and oxides, further accelerate abrasive wear of the tool. In addition, the chips are easily welded onto the tool, leading to the formation of built-up edge (BUE) <sup>10</sup>. Workpiece geometry can also have great influence on tool wear and machining efficiency when milling

of Inconel 718 curved surface parts<sup>11</sup>. It has been shown that change in cutting force due to variation of geometric features affects both tool wear and machined surface quality. All these factors adversely affect the tool life for machining Inconel 718. Inconel 718 is stated to be 16, 6 and 4 times more difficult to machine than aluminium, mild steel and stainless steel respectively<sup>12</sup>. Higher cutting forces in machining Inconel 718 demand tool materials, which have high wear resistance and toughness in order to avoid rapid tool deterioration or premature failure.

In order to achieve an economic tool life, it is vital to select right tool material, favourable tool geometry and optimum machining parameters (i.e., feed, speed and depth of cut). Machining of Inconel 718 in an efficient and economical way is always a challenge for the cutting tool industry owing to the short tool life. Tool materials for machining Inconel 718 include cemented carbides, ceramics, polycrystalline diamonds and cubic boron nitride. Cemented carbides tools are preferred, as they possess higher toughness compared to the others tools materials and are also economical to manufacture. Therefore, evaluation of machining performance of various carbide tools was subject to many scientific studies<sup>5, 10, 13</sup>. A detailed overview of the tool wear characteristic for different tool materials used to machine nickel based alloys is given by Zhu et al. and Akhtar et. al.<sup>14, 15</sup>. Flank wear, crater wear, chipping or fracturing and notching at the tool edge are found to be the dominating wear and failure modes when machining Inconel with the carbide tools due to a combination of high thermal and mechanical stresses. In general, abrasion, adhesion, BUE formation, diffusion and cracking were observed the common wear mechanisms in carbide tools during widely used Inconel machining processes such turning<sup>1, 5, 16-18</sup>, milling<sup>3, 10, 13, 19-21</sup> and drilling<sup>22-24</sup>.

In contrast to other sawing techniques, bandsawing is widely used in cutting off operations and offer competitive advantages of higher metal removal rate, lower kerf loss, better straightness of cut, competitive surface finish and a longer tool life. A number of scientific studies have been reported in the literature to provide an insight about bandsaw tooth design, mechanics of bandsawing, bandsaw performance and wear modes and mechanisms in bandsaw cutting edges <sup>25-28</sup>. Majority of these studies were focused on the bandsawing of steel workpieces with bimetal high-speed steel bandsaws <sup>29</sup>. However, very limited literature is available in public domain related to machining with carbide tipped bandsaws <sup>30-31</sup>.

Bandsaw blades for metal cutting are mainly of two kinds, bi-metal blades with the cutting edges made of high speed steel (HSS) and carbide bandsaws with tungsten carbide teeth. While carbide-tipped bandsaws have been developed for cutting difficult-to-cut materials, bi-metals are still the most widely used bandsaws for cutting off operations. The initial cost of a carbide bandsaws is approximately twice that of the bi-metal bandsaws but the cost per cut for carbide blades in most of the cases is much less than that for the bi-metal bandsaws <sup>32</sup>.

Carbide tipped bandsaws are very popular in cutting Nickel based superalloys such as Inconel 718. The main benefits of the carbide bandsaws over the bimetal bandsaws are long blade life owing to harder and more heat resistant carbide tips, higher productivity owing to higher feed rate, and lower cost per cut owing to higher sawing rate, lower downtime for blade changing etc. The sawing rate could be 3 times higher with carbide tipped bandsaw compared to bimetal bandsaw when machining Inconel <sup>32- 33</sup>.

With the requirements of new materials to meet demands of new and innovative products, the manufacturing engineers and hence the bandsaw users and suppliers have the tasks of cutting

these new materials efficiently and economically. Some progress has been made in the development of carbide bandsaws such as introducing improved carbide tip material, quality of tip surface and edge characteristics and tooth design <sup>33</sup>. However, it is important to gain an understanding of the fundamental nature of the cutting process, wear and failure modes and how they are influenced by depth of cut, tool material, workpiece materials and tool design associated with carbide tipped bandsawing. Although considerable efforts have been invested by the scientific community on the secondary machining (e.g., turning, milling, drilling etc.) of Inconel 718, very little or no attention is paid on machining of the same by the primary machining processes such as bandsawing. The aim of the current investigation is to study the machining characteristics of Inconel 718 with carbide tipped bandsaw teeth **under interrupted orthogonal turning condition**.

## **2. Experimental Procedure**

### 2.1. Workpiece Material

Inconel 718 was selected as the workpiece material for this investigation. The mechanical properties of Inconel 718 are presented in Table 1. The chemical composition of the workpiece material was measured by Energy Dispersive X-Ray Spectroscopy (EDX) (Table 2).

### 2.2. Cutting Tool

Single bandsaw teeth made of tungsten carbide tips were employed for the machining tests. Figure 1 presents a schematic diagram of a bandsaw tooth highlighting the tooth geometry. **The tooth geometry is designed to efficiently cut large and difficult-to-cut materials such as Inconel for production cutting end-users. High-grade backing steel, and carbide tip materials in the teeth with optimum cutting edge produced by fine grinding give superior workpiece**

surface finish, maximum tool life and premium bandsawing performance. All teeth were examined under an optical microscope and a Scanning Electron Microscope (SEM) for identifying any defects. The chemical composition of the carbide tooth was measured by EDX (Table 3). The geometrical features of the bandsaw teeth were measured by a shadowgraph and average values are presented in Table 4.

### 2.3. Cutting Test Procedure

It is well recognised that metal cutting testing and hence the acquisition of useful data for tool evaluation and tool design and development is time-consuming and costly. The problem is further exacerbated when attempting to gather useful data by carrying out scientific tests on tools having more than one cutting edge. As a multipoint cutting tool, it is not very convenient to conduct full product testing of bandsaw owing to the high cost associated with the workpiece, lengthy machining time and complexity of extracting information from the measured data. At the moment, no national or international standard for bandsaw performance testing is available. From the manufacturing point of view, even the most rigorous quality control system will not be able to maintain the consistency in tooth geometry in every single tooth of a band with hundreds of cutting edges. Therefore, it is not surprising that bandsawing test results obtained from blades using commercial bandsaw machines will vary. The performance and life of bandsaw blades can also be influenced by the bandsaw machine characteristics (machine dynamics) and operating parameters (feed, speed). This could influence test data and contribute to inconsistency in the test results. As a general practice, time per cut as well as monitoring indirect parameters such as increase in cutting forces, or amount of run-out of the saw kerf from the vertical plane are often used as bandsaw performance criteria. However, this only gives global data, which is difficult to apply to individual teeth. Therefore, a single tooth simulation test representative of a full product



performance test can give fundamental understanding of cutting mechanism, tool wear etc. and data required for optimising cutting conditions.

In the current research work, the performance of carbide tipped bandsaw tooth while cutting Inconel 718 was evaluated using a “single tooth technique”<sup>35</sup>. A schematic diagram of the machining test facility is presented in Figure 2. Separate workpiece sections were attached to the chuck to simulate the interrupted cutting action in bandsawing. Single tooth concept was also employed to understand other multipoint machining behaviour such as grinding of Inconel with a CBN grit<sup>36</sup>. A single tooth test needs to be fully representative of the ordinary bandsaw product testing. The results that are produced need to be meaningful in order to replace the full bandsaw testing. Previous research dealt with the initial cutting action of single bandsaw teeth and correlated the performance of single teeth to the performance of the full product. It was found that a single tooth test can be employed to simulate the initial cutting action of the full bandsaw<sup>35</sup>. However, despite having much similarity between the single tooth and full product tests, one should recognise some basic differences. For example, feeding bandsaw into workpiece is different in nature from that of a rigid lathe structure. The band saw can deflect under high feed rate pressure, which usually is not the case in more rigid set-ups such as lathe. In bandsawing, the depth of cut is determined by the force from the bandsaw and its cutting ability. Moreover, the width of the bandsaw can affect its cutting ability. Special attention should have been paid to the cross slide system in tool holder. Poor stiffness in the lathe cross slide system can produce backlash and hence there will be some degree of inconsistency in setting the depth of cut. Chips can move freely as no gullet was included in the single tooth and cutting takes place on the side of the workpiece in an open kerf situation unlike in actual bandsawing. These differences can affect the single tooth test results to some degree when compared with the full bandsawing.

Three different feeds per tooth or depths of cut (10  $\mu\text{m}$ , 20  $\mu\text{m}$  and 30  $\mu\text{m}$ ) with a constant speed of 30 m/min were chosen for the cutting tests. The width of cut was set to approximately 1 mm. Machining forces were measured during the bandsawing operation with a Kistler dynamometer and associated data acquisition equipment. Specific cutting energy was calculated from the force and material removal rate data<sup>27</sup>. The wear modes and mechanisms in the bandsaw teeth were investigated in the SEM. General characteristics chips and their surface morphology were studied under an optical microscope.

### 3. Results and Discussions

#### 3.1. Characteristics of New Bandsaw Tooth

Figure 3(a) presents a typical SEM image of a bandsaw tooth, showing both the clearance and rake faces. The close view of the cutting edge appears to be free of any defects such as chipping. The average edge radius of the cutting edge was 13  $\mu\text{m}$  when measured in the SEM. No sign of chipping was also observed in both rake and clearance faces. Horizontal grinding marks were clearly visible on the clearance face. However, no grinding marks were observed on the rake face due to an additional finishing operation performed during the bandsaw manufacturing process. This helps easy chip flow over the smooth rake face.

During the manufacturing process, the carbide bandsaw teeth were processed by a special edge modification operation to produce a small flat on the cutting edge. A diamond pad was pressed against the teeth while the band travelled slowly<sup>37</sup>. On average, the operation created a flat length of approximately  $120\ \mu\text{m} \pm 20\ \mu\text{m}$ . The modified edge reduces the vibration at the beginning of cutting with a shorter running-in period and a much lesser chance of chipping the brittle carbide tip. The generation of flat was clearly visible from the side view of the magnified edge creating a new angle with the rake face (Figure 3(b)). However, the flat

surface appeared to be substantially rougher than both the rake and clearance faces. The surface was characterised by ploughing marks created by the diamond particles (Figure 3(c)).

### 3.2. Wear Modes and Mechanisms of Bandsaw Tooth

SEM image of the worn bandsaw tooth clearly revealed that flank wear was the dominant wear mode (Figure 4(a)). The image also showed that chipping occurred on the rake face due to the interrupted nature of the cutting process. Furthermore, the flank wear at the right-hand corner of the tooth was more prominent than the rest of the cutting edge. This corner wear was caused due to the cutting action by the set tooth. Flank wear developed at the cutting edge due to the abrasive action between the flank face and machined workpiece (Figure 4(b)). There was also a clear evidence of adhesion of workpiece material onto the worn flanks promoting the adhesive type wear. This is also evident from Figure 5, which shows adhering workpiece on the side face as well as on the flank face. Evidence of plastic deformation at the corner of the tooth was also found possibly due to the high mechanical and thermal stresses generated at the cutting edge.

The formation of microcracks in carbide tool is often observed in intermittent machining operation and has been reported previously. Microcracks observed in the bandsaw cutting edges (Figure. 6(a)) could further extend into the carbide tip during prolonged machining and finally leading to chipping of the edge, thus modifying the tooth geometry <sup>38-40</sup>. The microcracks around the region of chipping propagate and can lead to subsurface fatigue cracks during prolonged machining. Owing to the poor thermal conductivity of the Inconel 718, very little heat is carried away by the chips or workpiece material. Therefore, a high temperature is generated at the tool-workpiece interface leading to welding of chips with the cutting edge as seen in Figure 6(b) <sup>41</sup>. The high chemical affinity of the Inconel further accelerates the

welding and adhesion of the workpiece material onto the cutting edge. This welding process again accelerates the tool wear through the gradual removal of tool material with the chip during the machining process. Figure 6(c) shows that, in certain cases, the strongly welded chip can remove a big chunk of the tool material leading to a significant modification of the cutting edge. It was also noticed that after prolonged machining at high feed rate (30  $\mu\text{m}$ ), the carbide tip was completely detached from the backing material as evidenced in the SEM image of the broken tooth (Figure 6(d)).

### 3.3. Built-up Edge Characteristics

After cutting approximately 500 sections ( $\sim 75$  m length of cut), a metal cap or built-up edge (BUE) started to form on the rake face of the tooth due to the welding of workpiece material by the high stress and temperature generated at the cutting edge (Figure 7(a)). As the machining progressed, the BUE gradually grew bigger in size as seen in Figure 7(b). The formation of built-up edge modified the cutting edge geometry leading to an effective blunt cutting edge with a higher edge radius, which would negatively affect the efficiency of the machining process. After continuing further cutting, it was observed that once the BUE reached a critical size, it was detached from the edge along with a fraction of tool material. This process further increased the wear at the cutting edge. Literature also reports the similar dynamic and cyclic BUE formation in three distinct stages (initiation, growth and breakage) <sup>42</sup> BUE formation can also be related to the periodic machine vibration possibly due to the significant reduction in the cutting ability of the modified cutting edge. The EDX analysis of the BUE revealed that the chemical composition of the BUE was similar to the workpiece material (Figure 7(d)). It was also interesting to note that on the rake face close to the carbide tip, the attached workpiece material apparently flowed in the gap between the BUE and rake face and formed a strong bond.

### 3.4. Chip characteristics

Chip formation mechanism plays an important role in determining the cutting forces, machining efficiency and the generation of the resulting machined surface. The chip formation mechanism in machining of Inconel 718 has been investigated in the past by a number of researchers <sup>18, 43-45</sup>. It is generally agreed that machining of Inconel produces serrated or saw tooth type chips, which is very different compared to that formed during machining of conventional materials such as copper, steel and aluminium. The localized shear deformation in the primary deformation zone causes adiabatic shear, which is responsible for the formation of serrated chips. The chip formation process is influenced by tool geometry (e.g., edge radius) and the machining parameters (e.g., feed, speeds and depth of cut).

The cutting edge condition of the bandsaw affects the chip formation process. At the new condition of the tooth, sharp cutting edge led to the formation of continuous chips indicating an efficient cutting process (Figure 8(a)). On the other hand, short lumpy chips were formed when the cutting edge became blunt with a higher edge radius (Figure 8(b)). By observing the chips formed during bandsawing under the SEM, it can be seen that the back surface of the BUE (Figure 9(a)) is smoother and shinier compared to the free surface (Figure 9(b)). This can be attributed to the high contact stresses and friction between the rake surface and the flowing chip <sup>45</sup>. On the free surface and side of the chip, it was noticed that very thin and closely packed lamellas were formed possibly due to micro level localised shear deformation (Figure 9(a) & 9(c)). In this case, the absence of pronounced serrated type chips can be explained by the fact that depth of cut, cutting speed, and the ratio between depth of cut to edge radius are much smaller in bandsawing compared to the conventional machining operations.

### 3.5. Cutting Force Measurement

It is a well-known fact that forces are strong indicator of cutting performances such as tool wear, surface finish, specific cutting energy etc. The development of cutting forces in the bandsaw teeth during the selected length of cut (150 m) at different feeds or depths of cut are plotted in Figure 10. The force components increased steadily with the length of cut, which indicated the gradual degradation and wear in the cutting edge. At the beginning of the machining test, the tool edge is relatively sharp and hence produces lower cutting forces<sup>46</sup>. As the test progresses, the edge wear increases leading to a blunt edge with increased contact area between the edge and the workpiece and also produces higher cutting forces. Therefore, the forces served as a good indicator of the degradation of the cutting edge throughout its life. Similar results were found by Sarwar et. al.<sup>25-26</sup> during the machining of steels with HSS bandsaws.

It was also noticed that at 10  $\mu\text{m}$  depth of cut, the cutting forces reached the peak point after cutting 90 m and then gradually decreased to lower values. It was evident that after cutting approximately 75 m, the workpiece material started adhering to the rake face forming a metal cap or BUE (see Figure 7). The BUE modified the geometry of the cutting edge (i.e., blunting and formation of higher edge radius) leading to higher forces in the tooth. Once the BUE was removed from the cutting edge, the forces started to decrease owing to the improved condition of the cutting edge or a decrease in depth of cut resulting from chipping or fracturing of the cutting edge<sup>3, 46</sup>. However, the forces at this point were still higher than the forces experienced by the carbide tooth at the start of the cutting operation possibly owing to the wear or chipping taken place at the cutting edge. Similar fluctuations in the cutting forces were also noticed during the tests with the other depths of cut employed.

The variation in force ratio (Cutting force,  $F_c$ /Thrust force,  $F_t$ ) with the length of cut is shown in Figure 11 and it is considered an important parameter since it can affect tool performance, tool wear and surface integrity of the machined surface. In all cases during the machining tests, the force ratio was less than one suggesting that the thrust force was higher than the cutting force. A number of factors can be associated with this unusual phenomenon with respect to bandsawing.

Firstly, it has been established that a rubbing or ploughing action could take place in the close proximity of the cutting edge, which in practice is not perfectly sharp<sup>47</sup>. This is the case in bandsawing where edge radius could be equal to or higher than the depth of cut. The wear generated on the cutting edge lead to edge blunting with further increase in edge radius. This results in a substantial increase in the thrust force component owing to the increased rubbing or ploughing action by the blunt edge<sup>46</sup>.

Secondly, the carbide bandsaw teeth in question have already a small flank ‘wearland’ owing to the honing operation. This could be responsible for higher thrust force than the cutting force even at the beginning of the cutting operation. With the increase in cutting length, the extended flank wear land led to even higher thrust force. Furthermore, it has been established that the thrust force is more sensitive to flank wear than the cutting force component and therefore, the greater is the flank wear, the higher is the thrust force.

Finally, the unique material characteristics of Inconel 718 could also play a role in showing characteristic of force ratio smaller than 1<sup>45, 48-50</sup>. A number of studies in the literature<sup>8, 9, 23, 51-52</sup> confirmed that Inconel 718 is sensitive to strain rate and gets rapidly work hardened. It was also found that the work hardening effect could be pronounced when the cutting tool is

worn <sup>53</sup>, thus making the removal of material even more difficult. The combination of higher edge radius compared to the depth of cut and worn tool condition in bandsawing can cause workpiece surface hardening and thus making the tool penetration into the workpiece difficult.

### 3.6. Specific Cutting Energy

Specific cutting energy ( $E_{sp}$ ) is defined as the energy required to remove a specific volume of workpiece material.  $E_{sp}$  is a quantitative way of measuring machining efficiency and can be used for assessing the condition of the cutting edge during cutting operation <sup>27</sup>. The  $E_{sp}$  parameter is particularly suitable for measuring bandsawing efficiency due to the low depth of cut compared to the bandsaw edge radius. Figure 12 presents the variation in specific cutting energy with the depths of cut at different cutting lengths. It is very clear from the figure that higher depth of cut reduces the specific cutting energy or improves the bandsawing efficiency. On average, a 45% decrease in specific cutting energy was observed with the increase in depth of cut from 10  $\mu\text{m}$  to 30  $\mu\text{m}$ . However, it should be noted that higher depth could result in a premature failure of the bandsaw teeth. This condition is not desirable in practical bandsawing point of view due to the fact that the failure of one tooth in a bandsaw loop can cause catastrophic failure of the entire bandsaw loop. It was also observed that  $E_{sp}$  at a particular depth of cut increases with the length of cut due to the wear and degradation of the cutting edge.  $E_{sp}$  is also more sensitive to a lower depth of cut as evidenced by a greater change in the  $E_{sp}$  values at 10  $\mu\text{m}$  depth of cut compared to that at 30  $\mu\text{m}$ . At 10  $\mu\text{m}$  depth of cut, cutting edge radius is equal to or even higher than the depth of cut.

The Higher depth of cut (30  $\mu\text{m}$ ) is clearly beneficial in terms of machining efficiency but not



suitable for machining Inconel 718. This can be explained by the fact that at a higher depth of cut, a combination of high cutting force and heat generated in the cutting tool causes the rapid degradation of the cutting edge and finally catastrophic failure of the tooth results. However, at a lower depth of cut, tool life can be significantly extended. Therefore, based on the  $E_{sp}$  results obtained with the range of parameters investigated, it can be concluded that depth of cut in combination with the other fixed cutting parameters should be lower than 20  $\mu\text{m}$  in order to achieve the reasonable productivity with minimum tool failure.

#### **4. Conclusions**

Comprehensive machining tests were carried out with carbide tipped bandsaw teeth in a specially designed test facility to ascertain the bandsawability of Inconel 718. During the machining tests, flank wear was identified as the dominant wear mode and evidence of chipping on the rake face and corner wear were also found. The mechanisms of flank wear involved a combination of abrasive and adhesive wear with some degree of plastic deformation. A built-up edge formed during the course of a machining test and increased the edge radius leading to an increase in the force components and a reduction in the machining efficiency. Although with the removal of the BUE, the force components decreased periodically, the carbide tip geometry was significantly altered due to the loss of edge material through chipping or welding with the BUE. The formation of micro-cracks on the cutting edge leading to chipping or fracture also played a significant role in the degradation of the carbide teeth. The wear and degradation of the cutting edge was indicated by the general trend of continuous increase in the cutting forces and specific cutting energies with the length of cut. The effect of the wear in the cutting edges was also observed through the change in generation of continuous chips at the new condition of the cutting edge to short lumpy chips at the end of the cutting test. Furthermore, it was evident that selection of higher

feed could improve the machining efficiency due to the reduction in specific cutting energy; however, this could cause premature failure of the carbide tip in the bandsaw tooth.

It should be noted that this preliminary bandsawability investigation was limited to only one cutting speed setting, which is generally used for practical bandsawing of the Inconel 718. In future, the effect of a full range of cutting speeds will be explored.

### **Acknowledgement**

The authors gratefully acknowledge the support from SNA Europe and Northumbria University, UK to carry out this research work.

### **References**

1. Fan Y, Hao Z, Lin J and Yu Z. New observations on tool wear mechanisms in machining Inconel 718 under water + air cooling lubrication cutting conditions. *J. Cleaner Prod.* 2015; 90: 381-387.
2. Sharman ARC, Hughes JI and Ridgway K. The effect of tool nose radius on surface integrity and residual stresses when turning Inconel 718TM. *J Mater Process Technol* 2015; 216: 123-132.
3. Zhang S, Li JF and Wang YW. Tool life and cutting forces in end milling Inconel 718 under dry and minimum quantity cooling lubrication cutting conditions. *J. Cleaner Prod.* 2012; 32: 81-87.
4. Cantero JL, Diaz-Alvarez J, Miguelez MH and Marin NC. Analysis of tool wear patterns in finishing turning of Inconel 718. *Wear* 2013; 297: 885-894.
5. Bhatt A, Attia H, Vargas R and Thomson V. Wear mechanisms of WC coated and uncoated tools in finish turning of Inconel 718. *Tribol. Int.* 2010; 43: 1113-1121.

6. Arunachalam R and Mannan MA. Machinability of nickel-based high temperature alloys. *Mach Sci Technol* 2000; 4: 127-168
7. Ezugwu EO, Wang ZM and Machado AR. The machinability of nickel based alloys: a review. *J Mater Process Technol* 1998; 86: 1-16.
8. Ezugwu EO and Tang SH. Surface abuse when machining cast iron (G-17) and nickel-base superalloy (Inconel 718) with ceramic tools. *J Mater Process Technol* 1995; 55: 63-69.
9. Ezugwu EO, Wang ZM, and Okeke CI. Tool Life and Surface Integrity When Machining Inconel 718 with PVD- and CVD-Coated Tools. *Tribol. Trans* 1999; 42: 353-360.
10. Krian HR, Sharman ARC and Ridgway K. Optimization of tool life and productivity when end milling Inconel 718 TM. *J Mater Process Technol* 2007; 189: 153-161
11. Ma J, Gao Y, Jia Z, Song D. and Si L., Influence of spindle speed on tool wear in high-speed milling of Inconel 718 curved surface parts, *Proc IMechE Part B: J Eng. Manuf.* 2016, :1-11
12. Ezugwu EO. Key improvements in the machining of difficult-to-cut aerospace superalloys. *Int. J. Mach. Tools Manuf* 2005; 45: 1353-1367
13. Razak NH, Chen ZW and Pasang T. Modes of tool deterioration during milling of 718Plus super alloy using Cemented tungsten carbide tools. *Wear* 2014; 316: 92-100.
14. Zhu D. Zhang X. and Ding H. Tool wear characteristics in machining of nickel-based superalloys. *Int. J. Mach. Tools Manuf* 2013; 64: 60-77.
15. Akhtar W, Sun J, Sun P, Chen W and Saleem Z. Tool wear mechanisms in the machining of Nickel based super-alloys: A review. *Front. Mech. Eng.* 2014; 9: 106-119
16. Devillez A, Le Coz G, Dominiak S and Dudzinski D. Dry machining of Inconel 718, workpiece surface integrity. *J Mater Process Technol* 2011; 211: 1590-1598.
17. Devillez A, Schneider F, Dominiak S, Dudzinski D and Larrouquere D. Cutting forces in

- dry machining of Inconel 718 with coated carbide tools. *Wear* 2007; 262: 931-942.
18. Thakur DG, Ramamoorthy B and Vijayaraghavan L. Study on the machinability characteristics of superalloy Inconel 718 during high speed turning. *Mater. Des.* 2009; 30: 1718-1725.
  19. Kasim MS. Che Haron CH. Ghani JA. Sulaiman M.A and Yazid MZA. Wear mechanism and notch wear location prediction model in ball nose end milling of Inconel 718. *Wear* 2013; 302: 1171-1179.
  20. Ucan İ. Aslantas K and Bedir F. An experimental investigation of the effect of coatings material on tool wear in micro milling on Inconel 718 super alloy. *Wear* 2013; 300: 8-19.
  21. Ucan İ. Aslantas K and Bedir F. The performance Of DLC-coated and uncoated ultra-fine carbide tools in micromilling of Inconel 718. *Precis. Eng.* 2015; 41: 135-144
  22. Chen YC and Liao YS. Study of wear mechanisms in drilling of Inconel 718 superalloy, *J Mater Process Technol.* 2003; 140: 269-273.
  23. Sharman ARC. Amarasinghe A and Ridgway K. Tool life and surface integrity when drilling and hole making in Inconel 71. *J Mater Process Technol* 2008; 200: 424-432.
  24. Imran M. Mativenga P.T. Gholinia A. and Withers PJ. Comparison of tool wear mechanism and surface integrity for dry and wet micro-drilling of nickel based alloys. *Int. J. Mach. Tools Manuf* 2014; 76: 49-60.
  25. Sarwar M. Persson M and Hellbergh H. Wear and failure modes in bandsawing operation when cutting ball bearing steels. *Wear* 2005; 259: 1144-1150.
  26. Sarwar M. Persson M and Hellbergh H. Wear of the cutting edge in the bandsawing operation when cutting austenitic 17-7 stainless steel. *Wear* 2007; 263: 1438-1441.
  27. Sarwar M. Persson M and Hellbergh H and Haider J. Measurement of specific cutting energy for evaluating the efficiency of Bandsawing different workpiece materials. *Int. J. Mach. Tools Manuf* 2009; 49: 958-965.

28. Andersson C. Bandsawing. Part III: stress analysis of saw tooth microgeometry. Int. J. Mach. Tools Manuf, 2001; 41: 255-263.
29. M Sarwar, M Persson, H Hellbergh, J Haider, Forces, wear modes, and mechanisms in bandsawing steel workpieces, P IMech Eng B-J Eng Manufact, 2010, 224: 1655-1662.
30. Khan FN. Daadbin A. Persson M. Haider J and Hellbergh H. Assessing the performance of TiAlSiN coating on bandsaw tooth when cutting Ti-17 alloy. P IMech Eng B-J Eng Manufact, 2012; 226: 870-877.
31. Khan FN. Daadbin A. Persson M. Haider J. Development of AlTiN coated carbide bandsaw for machining titanium-17 alloy. Int. J. Surf. Sci. Eng. 2014; 8: 11-27.
32. Duffy P. Sawing the moody metal, Welding Design, www.weldingdesign.com, February 2006.
33. Hellbergh H. Sawing superalloys. Foundry Management & Technology 2003; pp. 34-36.
34. ASM Handbook Volume 2, Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, 10th Edition, Metals Park OH: ASM, 1994.
35. A.R. Doraisingam, Simulation of the intermittent cutting action of a bandsaw blade, PhD thesis, 2003, Northumbria University, Newcastle, United Kingdom.
36. Opoz TT and Chen X, Experimental study on single grit grinding of Inconel 718, 20 Proc IMechE Part B: J Eng. Manuf, 2015, 229:713–726
37. Forsberg P. Hellbergh H and Hayden RC. Bandsaw blade for metal and a method for manufacturing a bandsaw blade with teeth, Patent No. US 7908954.
38. Rahim EA and Sharif S. Tool failure modes and wear mechanism of coated carbide tools when drilling Ti-6Al-4V. Int J Precision Technol 2007; 1: 30-39.
39. Su Y. He N. Li L. and Li XL. An experimental investigation of effects of cooling/lubrication conditions on tool wear in high-speed end milling of Ti-6Al-4V. Wear 2006; 261: 760-766.

40. Ezugwu EO and Okeke CI. Tool life and wear mechanisms of TiN coated carbide tools in an intermittent cutting operation. *J Mater Process Technol* 2001; 116: 10-15.
41. Kitagawa T. Kubo A and Maekawa K. Temperature and wear of cutting tools in high-speed machining of Inconel 718 and Ti-6Al-6V-2Sn. *Wear* 1997; 202: 142-148.
42. Ning F. Pai PS and Mosquea S. The effect of built-up edge on the cutting vibrations in machining 2024-T351 aluminum alloy. *Int. J. Adv. Manuf. Technol.* 2010; 49: 63-71
43. Ozel T and Ulutan D. Effects of machining parameters and tool geometry on serrated chip formation, specific forces and energies in orthogonal cutting of nickel-based super alloy Inconel 100. *P I Mech Eng B-J Eng* 2014; 228: 673-686.
44. Dong G. Zhaopeng H. Rongdi H. Yanli C and Muguthu J.N. Study of cutting deformation in machining nickel-based alloy Inconel718. *Int. J. Mach. Tools Manuf* 2011; 51: 520-527.
45. Zhang S. Li J. Zhu X and Lv H. Saw-Tooth Chip Formation and Its Effect on Cutting Force Fluctuation in Turning of Inconel 718. *Int J Precis Eng Manuf* 2013; 14: 957-963.
46. Wang J. Huang CZ and Song WG. The effect of tool flank wear on the orthogonal cutting process and its practical implications. *J Mater Process Technol* 2003; 142: 338-346.
47. Knight W and Boothroyd G. *Fundamentals of Metal Machining and Machine Tools*, 3rd Edition, Taylor and Francis, CRC Press, Florida, 2005.
48. Fang N and Wu Q. A comparative study of the cutting forces in high speed machining of Ti-6Al-4V and Inconel 718 with a round cutting edge tool. *J Mater Process Technol* 2009; 209: 4385–4389
49. Fang N. Slip-line modelling of machining with a rounded-edge tool—Part I: new model and theory. *J. Mech. Phys. Solids* 2003; 51: 715-742.
50. Fang N and Wu Q. The effects of chamfered and honed tool edge geometry in machining of three aluminum alloys. *Int. J. Mach. Tools Manuf* 2005; 45: 1178-1187

51. Pawade R.S. Joshi SS and Brahmankar PK. Effect of machining parameters and cutting edge geometry on surface integrity of high-speed turned Inconel 718. *Int. J. Mach. Tools Manuf* 2008; 48: 15-28.
52. Joshi SV. Vizhian SP, Sridhar BR and Jayaram K. Parametric study of machining effect on residual stress and surface roughness of nickel base super alloy UDIMET 720. *Adv Mat Res* 2008; 47-50: 13-16.
53. Sharman ARC. Hughes JI and Ridgway K. Workpiece surface integrity and tool life issues when turning Inconel 718<sup>TM</sup> nickel based superalloy. *Mach Sci Technol*, 2006; 8: 399-414.

## List of Figure Captions

Figure 1. Schematic diagrams of (a) Bandsaw sample and (b) Carbide tooth tip geometries

Figure 2. Schematic diagram of the machining test facility

Figure 3. (a) Close view of the bandsaw cutting edge, (b) Side view of honed face and (c) Top view of honed surface

Figure 4. (a) Wear modes and (b) Wear mechanisms in carbide tipped bandsaw teeth

Figure 5. Adhesion of the workpiece (a) On the side face of tooth corner and (b) On the flank face

Figure 6. (a) Micro-crack formation on the rake face (b) Welded area between rake face and Built-up edge (BUE) (c) Cutting edge after removal of the BUE and (d) Catastrophic failure of carbide tip

Figure 7. Metal cap or BUE formation due to the adhering of workpiece material to the carbide tooth when machining Inconel 718 (a) Side view: starting of BUE (b) Side view: fully formed BUE and (c) Top view of BUE and (d) EDX elemental map of BUE

Figure 8. (a) Continuous chips and (b) Fragmented chips generated at the new and worn conditions of the bandsaw teeth respectively (Magnification  $\times 10$ )

Figure 9. Chip surface morphology (a) Top surface (not in contact with rake face) (b) Rear surface (in contact with the rake face) and (c) Side view

Figure 10. The variation in cutting forces with the length of cut at different depths of cut

Figure 11. The variation in force ratio (Cutting force/Thrust force) with the length of cut at different depths of cut

Figure 12. The variation in specific cutting energies with the depths of cut at different lengths of cut



Figure 1. Schematic diagrams of (a) Bandsaw sample and (b) Carbide tooth tip geometries

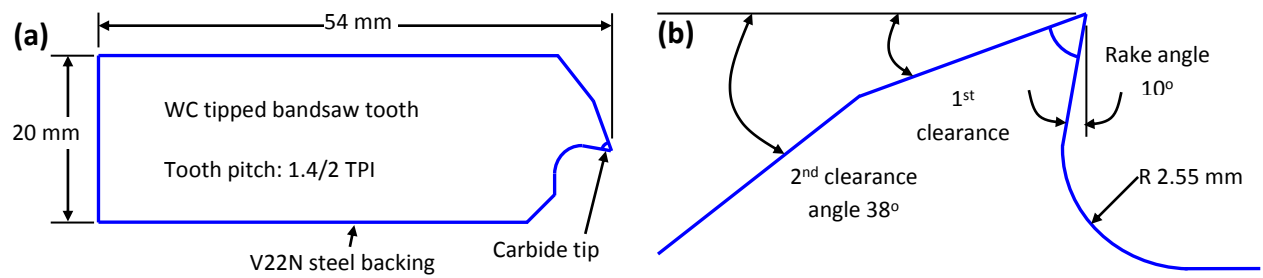


Figure 2. Schematic diagram of the machining test facility

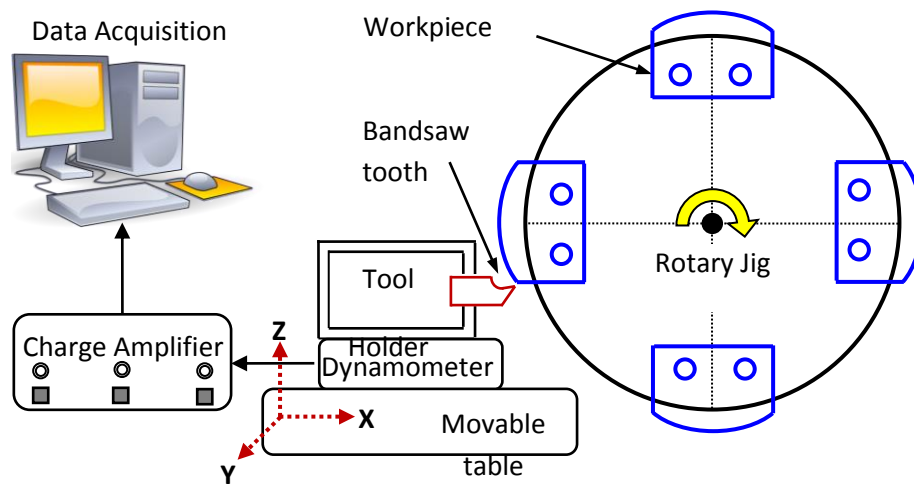


Figure 3. (a) Close view of the bandsaw cutting edge, (b) Side view of honed face and (c) Top view of honed surface

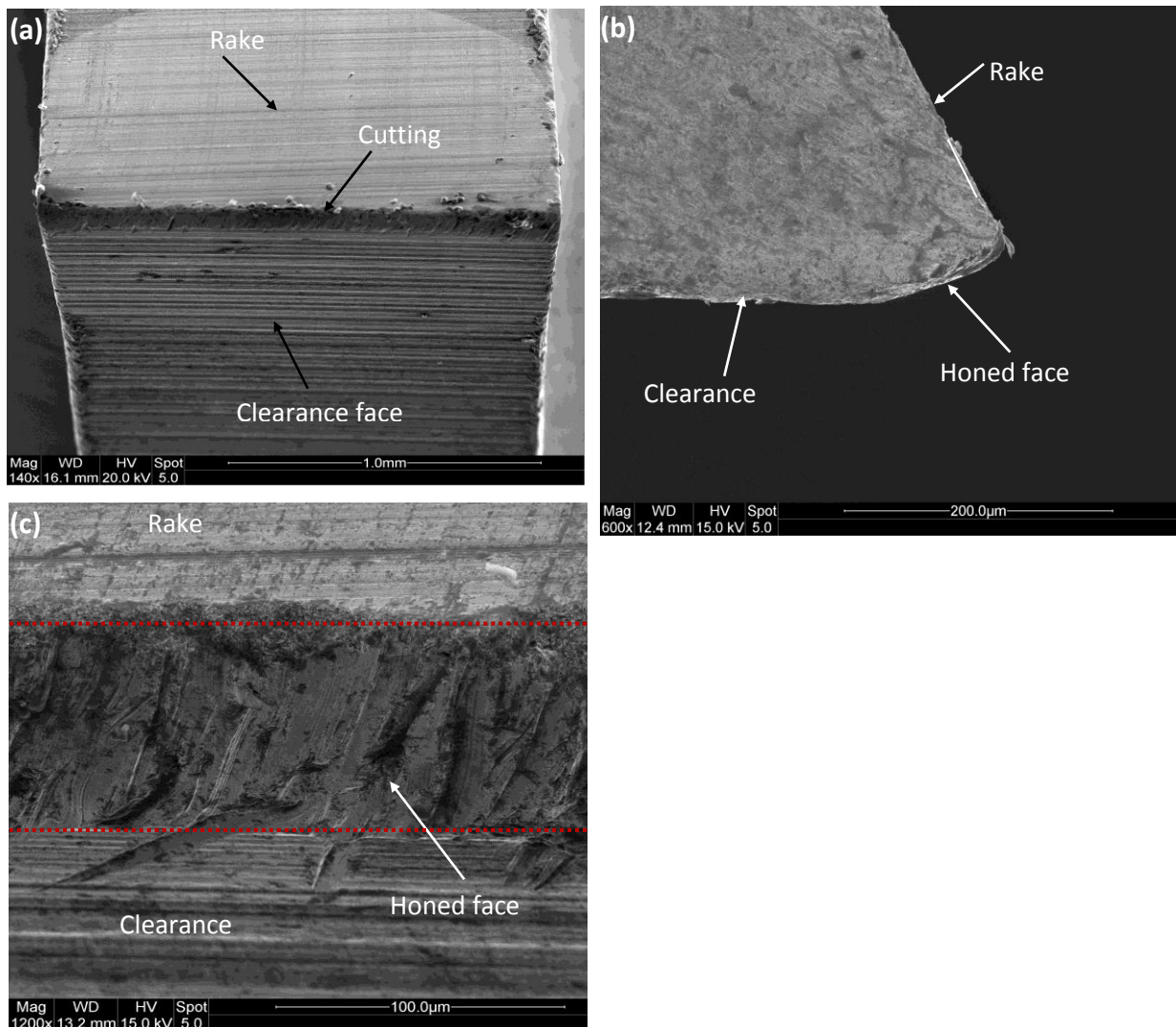


Figure 4. (a) Wear modes and (b) Wear mechanisms in carbide tipped bandsaw teeth

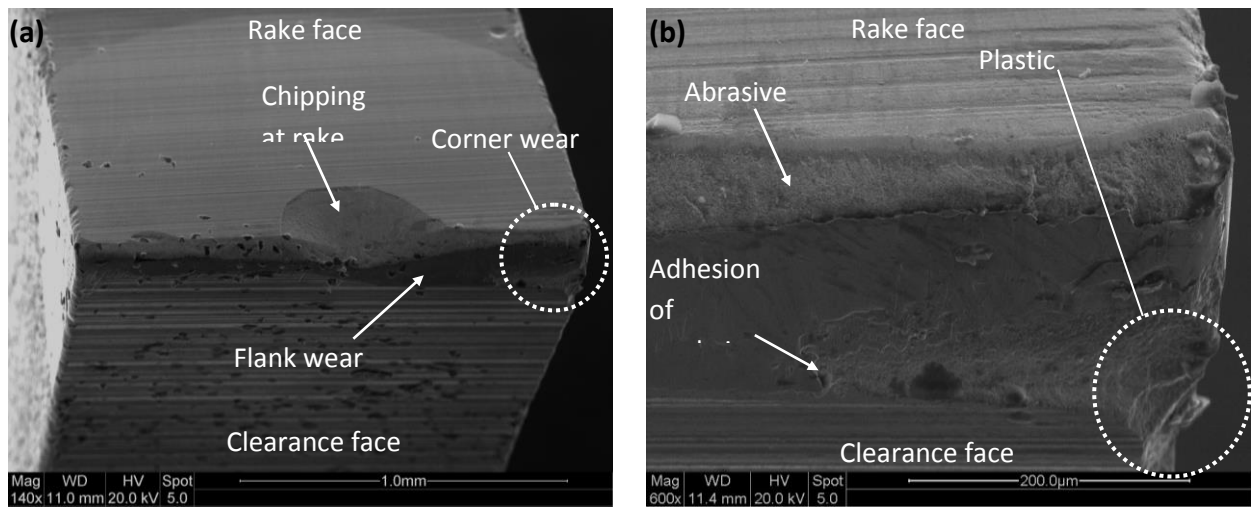


Figure 5. Adhesion of the workpiece (a) On the side face of tooth corner and (b) On the flank face

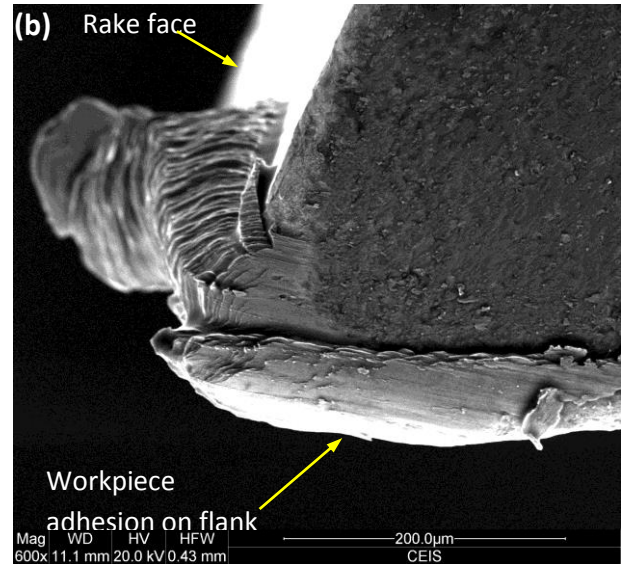
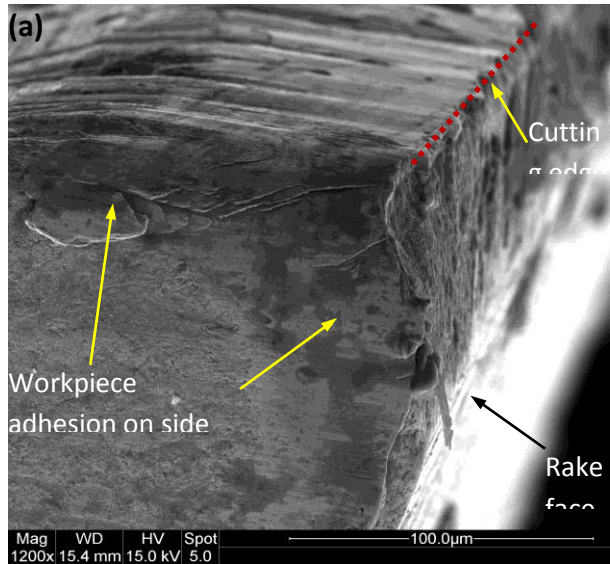


Figure 6. (a) Micro-crack formation on the rake face (b) Welded area between rake face and Built-up edge (BUE) (c) Cutting edge after removal of the BUE and (d) Catastrophic failure of carbide tip

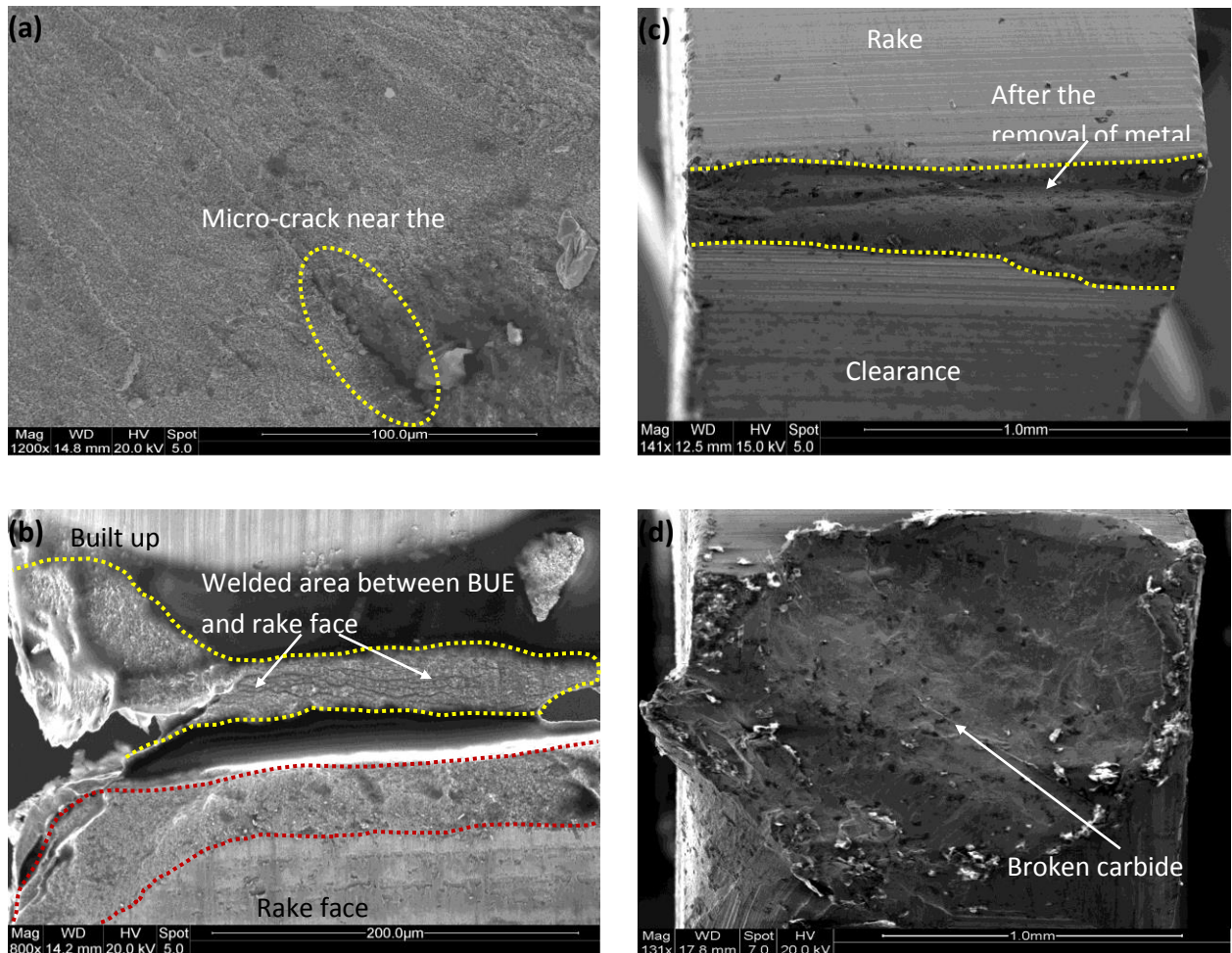




Figure 7. Metal cap or BUE formation due to the adhering of workpiece material to the carbide tool when machining Inconel 718 (a) Side view: starting of BUE (b) Side view: fully formed BUE and (c) Top view of BUE and (d) EDX elemental map of BUE

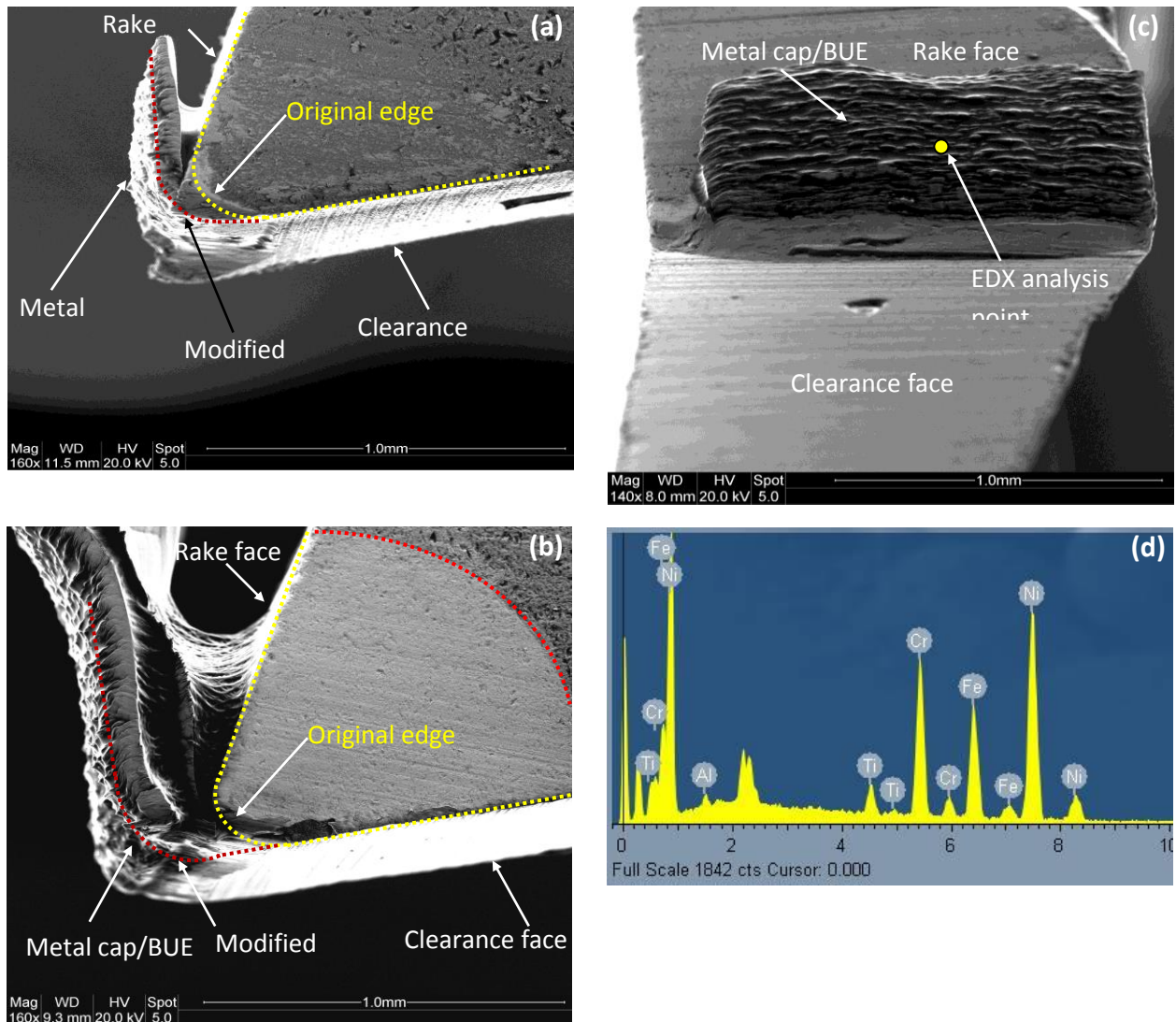


Figure 8. (a) Continuous chips and (b) Fragmented chips generated at the new and worn conditions of the bandsaw teeth respectively (Magnification  $\times 10$ )

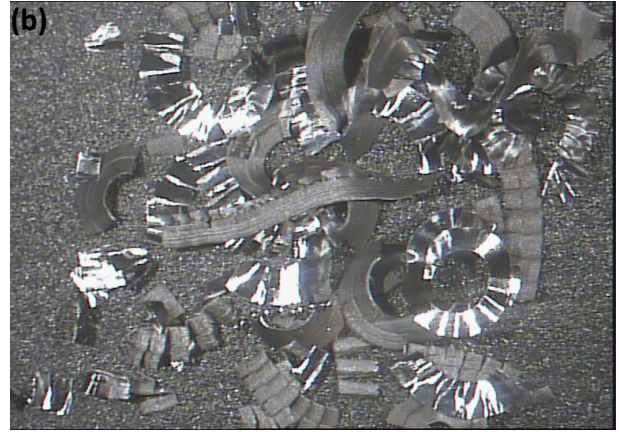
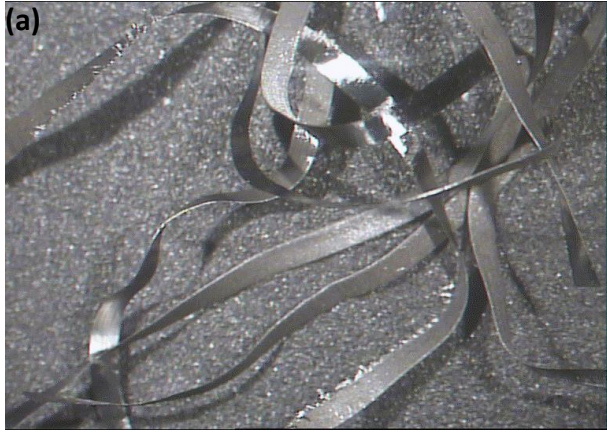




Figure 9. Chip surface morphology (a) Top/free surface (not in contact with rake face) (b) Rear surface (in contact with the rake face) and (c) Side view

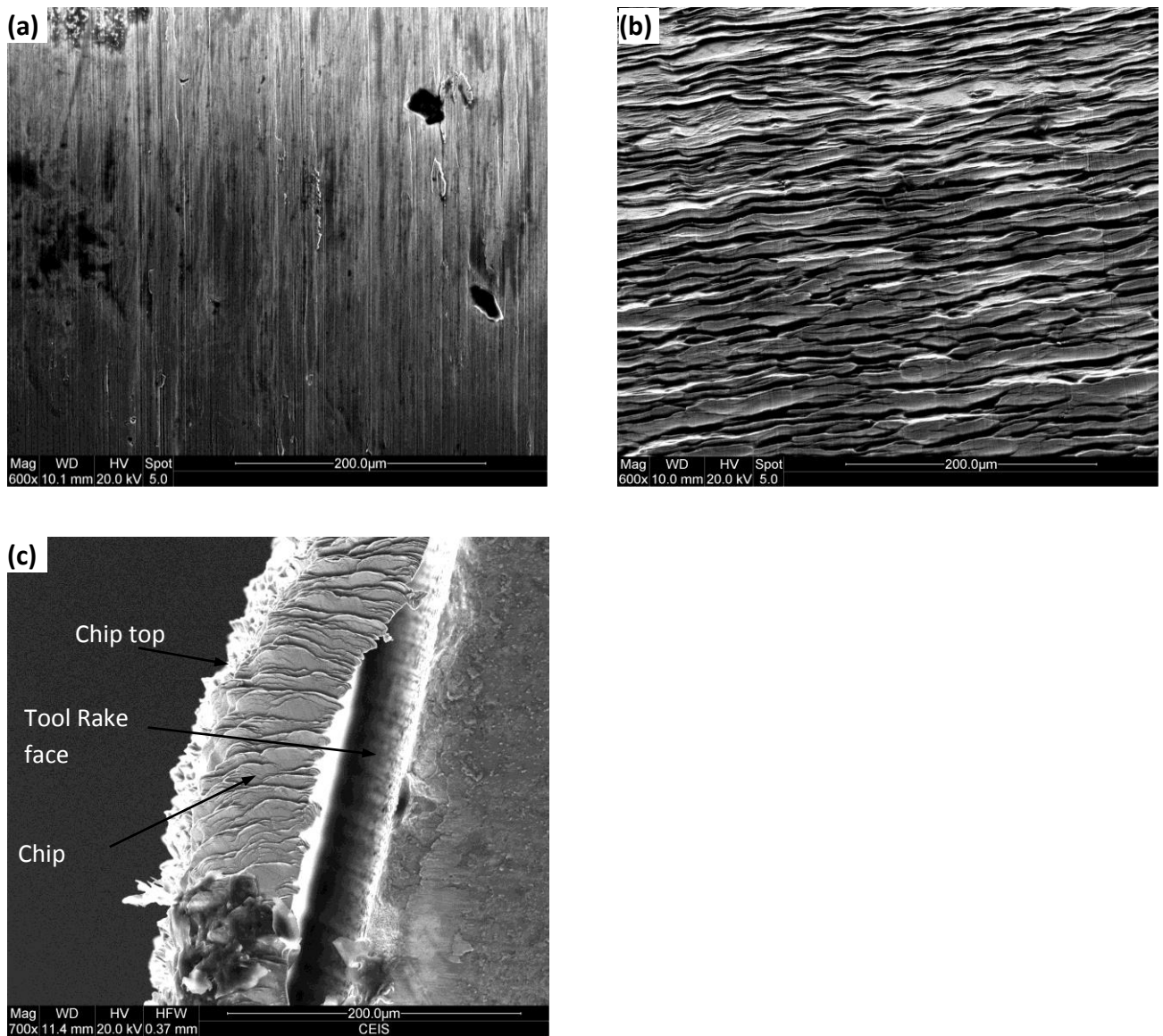


Figure 10. The variation in cutting forces with the length of cut at different depths of cut

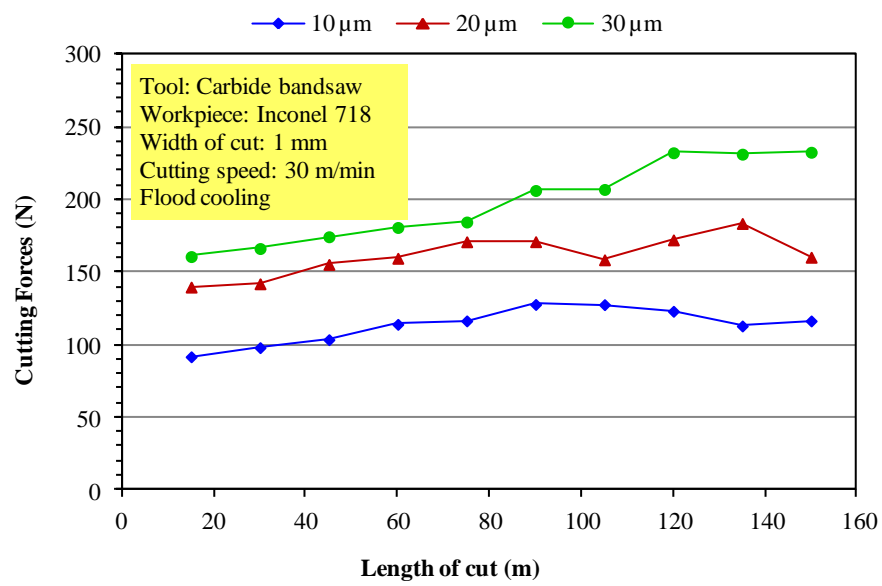


Figure 11. The variation in force ratio (Cutting force/Thrust force) with the length of cut at different depths of cut

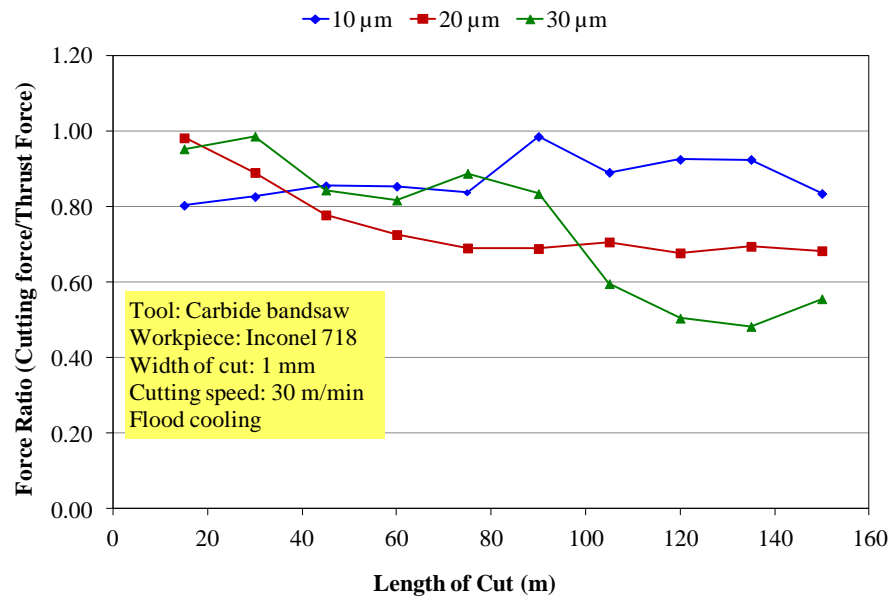
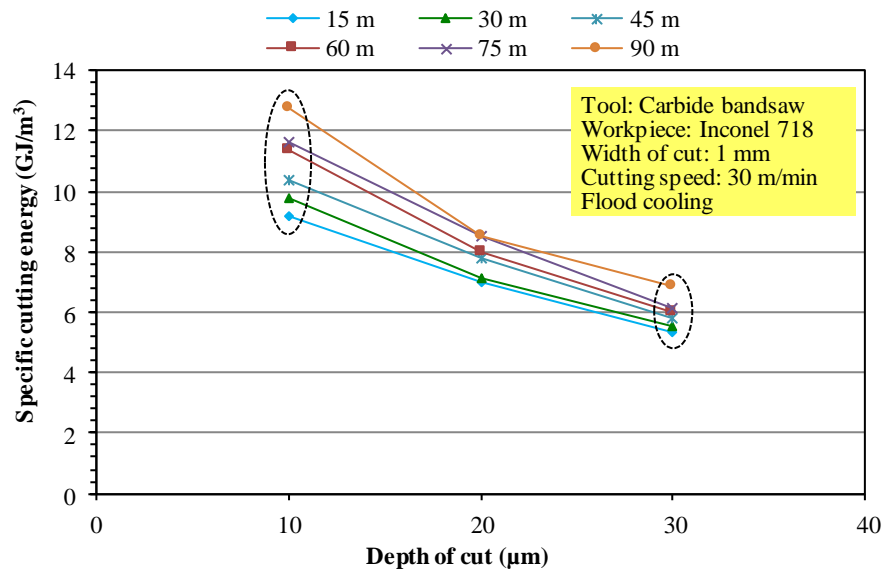


Figure 12. The variation in specific cutting energies with the depths of cut at different lengths of cut



## List of Tables

Table 1. Mechanical properties of Inconel 718<sup>34</sup>

Table 2. Chemical composition (wt%) of Inconel 718 measured by EDX

Table 3: Chemical Composition (wt%) of Tungsten Carbide Cutting Edge measured by EDX

Table 4. Geometrical characteristics of carbide tipped bandsaw

*Table 1. Mechanical properties of Inconel 718 [32]*

Ultimate tensile strength (MPa)	Yield strength (MPa)	Hardness (HRC)
1240	1036	36

*Table 2. Chemical composition (wt%) of Inconel 718 measured by EDX*

Ni	Mo	Ti	Cr	Co	Al	Mn	Fe
50-55	2.8-3.3	0.6-1.15	17-21	1.1	0.2-0.8	0.35	Bal.

*Table 3: Chemical Composition (wt%) of Tungsten Carbide Cutting Edge measured by EDX*

Co	W	C
18.94	14.15	66.91

*Table 4. Geometrical characteristics of carbide tipped bandsaw*

<b>Bandsaw tooth characteristics</b>	<b>Description</b>
Tooth pitch	1.4/2 TPI
Average thickness of cutting edge	1.61 mm
Length of a single bandsaw tooth	54 mm
Width of a single bandsaw tooth	20 mm
Average rake angle	9.8°
Average clearance angle	20.1°
Average set magnitude	0.58 mm